Statistical Modeling for U-Nb Aging and Lifetime Prediction

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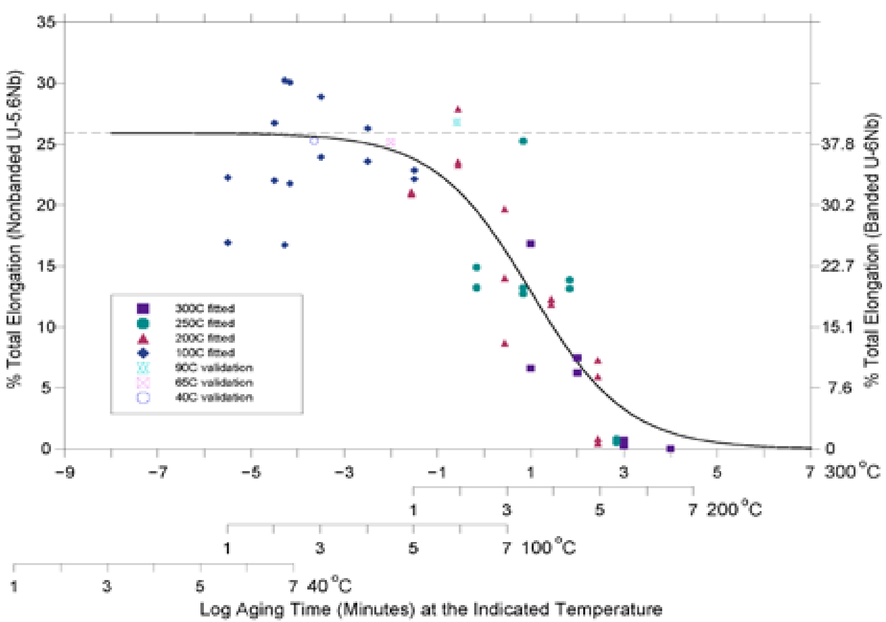
The Enhanced Surveillance Campaign of NNSA's Advanced Simulation and Computing program supports many basic scientific studies that help stockpile stewardship. One important study concerns aging during long-term stockpile storage of the uranium alloy 6 wt% niobium (U-6Nb) [1,2]. Long-term aging may change the microstructure and properties of U-6Nb alloy components in ways adversely affecting performance. Traditional approaches to modeling based on fundamental physics are not feasible due to limitations in the understanding of the scientific fundamentals of age hardening [3,4]. Statistical modeling provides a way to develop empirical predictive models for such data where first-principle models for complex physical mechanisms are not available.

Fig. 1. Universal age-hardening plot of U-5.6Nb TE data (solid symbols—fitting data from non-banded U-5.6Nb, open symbols—validation data from banded U-6Nb) and model fit to data (solid line). Alternate x-axes showing equivalent times at different temperatures are also shown. For reference, 10^5 minutes ≈ 69 days and 10^7 minutes ≈ 19 years.



We developed statistical models relating age-sensitive properties to time and temperature, drawing upon a large body of artificial aging data obtained from nonbanded U-5.6Nb and U-7.7Nb material [5]. These two nonbanded alloys represent the average (U~5.8Nb) and upper limit (U~8Nb) of compositions present on 100- to 200-µm length scales in the banded U-6Nb material. There was concern that the high Nb bands would age faster and cross the failure threshold sooner than the mean or lower Nb bands. Thus, the high Nb (U-7.7Nb) band behavior would be the life-limiting factor for banded U-6Nb.

The aging response was tracked in U-5.6Nb and U-7.7Nb indirectly through the observed time-dependent changes in various mechanical properties. The following age-sensitive properties were measured at ambient temperature following artificial ages at 100ºC, 200ºC, 250ºC, and 300ºC: total plastic elongation, uniform elongation, first-yield strength, first-yield modulus, second-yield strength, ultimate tensile strength, and Vickers hardness.

Figure 1 shows our approach of collapsing the data from the four accelerated aging temperatures onto a universal aging response. This unique approach is based on the assumption of Arrhenius behavior governing the equivalencies of various time-temperature combinations. A separate term is included in the model to quantify the shift from one time-temperature domain to another. This allows the effects of both time and temperature on aging response to be assessed simultaneously.

The model also enables predicted curves to be produced at temperatures other than those at which data was obtained. Figure 2 provides an example of the model fit and extrapolations to lower temperatures for the property total elongation. In this plot, the time-temperature curves are plotted individually for each aging temperature. For each of the predicted curves in the plot, 95% confidence intervals are provided.

Reasonable model fits to artificial aging data for each of the properties in the U-5.6Nb and U-7.7Nb alloys were obtained, although the models fit some of the measured properties better than others. Useful age-sensitive property predictions were obtained for most of the elastic, strength, ductility, and hardness properties studied. The U-5.6Nb models were more robust and therefore are expected to have better predictive power than those of the U-7.7Nb models, especially at the lower aging temperatures of interest. Model extrapolations to longer times (up to 5 years) and lower temperatures (as low as 40ºC) than those used for the model fitting agreed well with most of the validation data gathered for both nonbanded alloys, as well as banded U-6Nb, giving provisional validation of the fitted models.

In addition, the lifetime for each alloy at a variety of aging (storage) temperatures was evaluated, based on the failure criterion for the property total elongation. The error associated with the model fits provides 95% confidence intervals, which give the upper- and lower-bound lifetime estimates. From Fig. 2, the lifetimes can be obtained by finding the point at which a given predicted curve crosses the failure threshold (the yellow line).

Research such as this is essential for the understanding of our aging weapons systems. Studies concerning fundamental materials and material properties are crucial to decision making regarding the stockpile.

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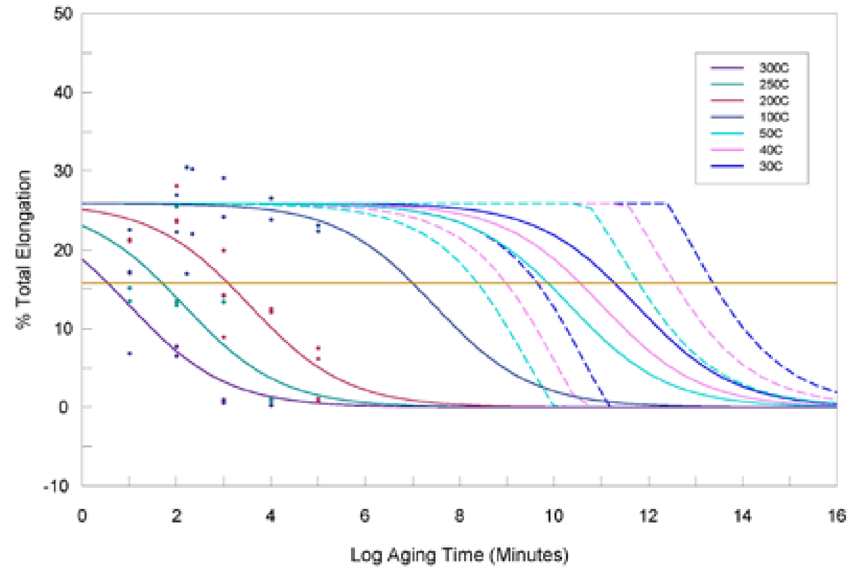

Fig. 2. U-5.6Nb TE fitting data (points), model fits to data at the artificial aging temperatures employed (solid lines), and low-temperature model predictions (solid line—mean, dashed lines—95% confidence intervals). The yellow line is the failure threshold.

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